IOP Conf. Series: Materials Science and Engineering **966** (2020) 012014 doi:10.1088/1757-899X/966/1/012014

Double-sided arc welding with multiple electrodes of vertical joints of steel tanks

O I Filippov[1, 5], V A Erofeev[2], S I Poloskov[3] and A Yu Melnikov[4]

[1] Transneftstroy Co. Ltd, Moscow, 127254, Russia
[2] Tula State University, 92, Lenina Avenue, Tula, Russia, 300600
[3] Bauman Moscow State Technical University, 5, ul. Baumanskaya 2-ya, Moscow, 105005, Russia
[4] SHTORM Co.Ltd, Ekaterinburg, 620100, Russia

E-mail: [5] foi_1@rambler.ru

Abstract. The increase of the welding productivity is still of immediate interest, which in turn requires the development and implementation of more high-performance welding methods that ensure a consistently high quality of welded joints. One of the ways to further increase the productivity of arc welding processes in the construction of tanks is the industrial use of automatic double-sided arc welding with multiple electrodes in separate weld pools.To establish the relationship between the parameters of the welding mode, energy characteristics, as well as the distance between the torches and their angle of inclination relative to the groove, a physical and mathematical model of the production of the welding joint when four arcs participate in pairs from both sides of the joint has been developed. Thus, computer modeling showed that during weld formation with the movement of the electrode down (vertical down), the possibility of supplying each pair of arcs with pulsed current should be taken into account. During groove filling with the movement of the electrodes up (vertical up), their lateral oscillations and delays at the edges should be carried out according to an aperiodic law in order to minimize the effects of 'magnetic blow'.

1. Introduction

Taking into account a number of advantages, including the simplicity of manufacturing, operation and maintenance, occupied space, vertical steel tanks for storing oil and oil products are one of the most popular and widespread varieties of tanks and vessels.Therefore, the Russian Federation has developed an extensive program for the construction of new tanks and maintaining high operational requirements for already constructed tanks. Unfortunately, tanks for receiving, storing, processing and dispensing of oil and oil products are dangerous industrial facilities, accidents at which can lead to serious material, environmental and social consequences. Therefore, for their construction, high requirements are imposed on all stages of their production, including the quality of welding works, since the analysis showed that the safe operation of the tanks is significantly affected by defects in welded joints [1].

The design of the tank includes a bottom, a shell and a fixed roof. Assembly and welding of metal structures of the bottom and shell of tanks is carried out on a previously prepared foundation slab and base. Metal structures can be made in two ways: by rolling or sheet assembly. It is also possible to produce them by a combined method. However, the accumulated experience of building tanks by the rolling method convincingly showed that such method is the most appropriate for the production of tanks with a shell thickness of not more than 8 mm; therefore, sheet-metal assembly and welding [2]

IOP Conf. Series: Materials Science and Engineering **966** (2020) 012014 doi:10.1088/1757-899X/966/1/012014

became the main method for construction of large-capacity tanks. Currently, fusion arc welding is the most commonly used method for tanks assembling. Welding of inlets, ventilation pipes, manholes is performed by mechanized welding with a consumable electrode in active gases and gas mixtures. When performing the most time-consuming operations, which include production of a bottom corner weld connecting the bottom to the shell of the tank, welding of horizontal and vertical seams during sheet assembly, both mechanized and automatic welding are used [3, 4]. It is known [5, 6], that vertical seams are one of the weakest structural and technological units of tanks, since they account for about 15% of the total number of detected defects.

For now, the used technologies have reached their maximum performance. This occurs due to restrictions on the size of the weld pool and heat input into the welded joint. Productivity increase of welding works is still of immediate interest.

In our opinion, a promising way to further increase the productivity of arc welding during the construction of tanks is the industrial use of automatic two-arc double-sided welding in separate weld pools [7], since it is quite problematic to keep a weld pool of large volume and mass during production of vertical joints.Significant advantage of the proposed welding method is the fact that with the simultaneous exposure of a pair of arcs on both sides of the joint, additional phenomenon are achieved: during root welding, it is strengthened by an additional layer of electrode metal, and during filling of the grooves, thermal cycling of the weld and heat-affected zone (HAZ) is performed.

However, such complicated technological methods, as well as the spatial position of the weld pool, affect the distribution and amount of energy input, and, consequently, the quality of the joints [8]. Therefore, for the industrial use of the proposed technology of automatic double-sided arc welding with multiple electrodes of vertical joints, it is necessary to define scientifically-based requirements for technologies and equipment. In this case, it is necessary to establish the relationship of a large number of parameters: welding speeds and wire feed speed; energy characteristics of the process and heat input during welding; values of voltages and currents of arcs; parameters of current pulses and lateral oscillation of the welding torches; the distance between the torches and their angle of inclination relative to the groove.

2. Materials andMethods

To solve this class of problems, it is necessary to create a physical and mathematical model of the process, its computer implementation, and assessment of its adequacy. In the case of positive results, further research is possible to determine the range of acceptable values of welding parameters and their optimization, to study the sensitivity of the process to instability of parameters in the neighborliness of optimal values. The necessary source data for modeling the features of this type of multi-arc welding of vertical joints will be the thermophysical properties of steel and electrode wires, the thickness and geometric characteristics of the beveling, the location of the torches relative to the joint, the welding and feeding speeds of the electrodes, the diameters of the electrode wires.

Since in the proposed welding type four arcs participate in pairs from both sides of the joint, based on their interaction, the model will determine the equilibrium conditions of the weld pools in the modeling space limited by physical phenomena, Figure 1.

Based on preliminary work, it was determined that the formation of the root of the seam should be carried out with the synchronous movement of the torches down (vertical down), while filling the grooves with their movement up (vertical up). Therefore, the formation of the weld root was ensured by welding vertical down, with the location of each pair of arcs from different sides of the joint, Figure 1b. In this case, the second arc of each one-sided pair (Figure 1a) should be placed at a distance L_{ef}, to exclude the fusion of the weld pool. When forming a two-sided seam with synchronous exposure of arcs, electrode wires with a diameter of d_e (Figure 1b) are fed at a speed v_e on both sides of the X-groove (Figure 1c). Welding torches are placed at an angle β to the longitudinal section of the weld (Figure 1b), which ensures the highest electrodynamic pressure of the welding arcs and contributes to better retention of the melt of the weld pool. For root formation, it is advisable to use pulsed welding [9, 10], which initiates the fusion of the groove faces and retention of the weld pool in the groove, as well as minimizing the effect of magnetic blow on the wandering of arcs and spatter of electrode metal.When filling out a groove, to reduce the likelihood of a weld pool dripping, it is advisable to weld with lateral oscillation of the electrode (Figure 1d) and delays at the toes of the grooves, which reduce the length of the weld pool while keeping the power of the arc and reduce the likelihood of lack of penetration at the toes of the groove. Thus, the simultaneous activity of all four arcs from different sides of the joint provides a significant increase in the productivity of welding of vertical joints of steel tanks.

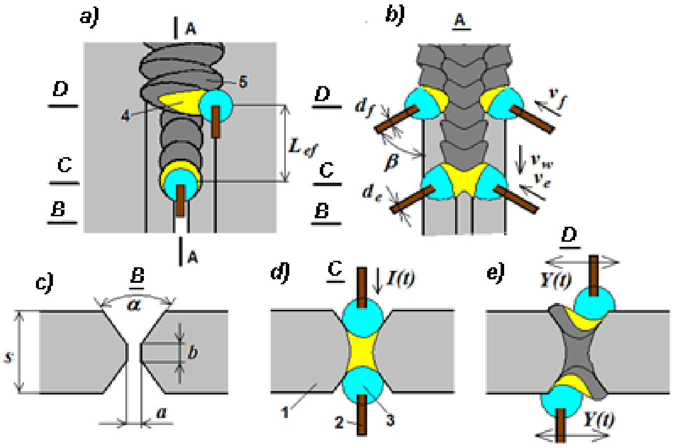

Figure 1. The schematic of the implementation of welding of vertical joints (a, b), cross section of the joint (c), and position of electrodes relative to the joint (g): 1 – parts of a groove weld; 2 – electrode wire; 3 – arc; 4 – weld pool; 5 – weld seam.

Considering these features of the multi-arc welding process, an area is selected for modeling physical phenomena, covering the edges to be welded and the weld pool formation zones. An important feature is the uncertainty in the structure of the modeling area, determined by the formation of the weld pool and seam. This causes the need to adjust the structure of an area depending on the results of the model equations. The morphology of the area is expressed within a Cartesian coordinate system of *x, y, z*-coordinates by the membership function of the points belonging to different zones, the properties and processes in each are different. Initially, the structure of the modeling area is determined by the geometry of the beveling (zone M_m). As the groove is filled with electrode metal, the molten zones of the weld pool M_L, solid-liquid metal M_s, and weld metal M_w arise. The listed zones are in contact with the gas environment *G*. The affiliation of a point to one of the zones is determined by the state of the metal. For example, points of a metal with a temperature below the solidus temperature belong to the M_m, zone, and above the liquidus temperature, they belong to the M_L zone. Internal interband surfaces are marked as intersections of the sets of points belonging to the corresponding zones. For example, the location of points $(x,y,z)_L$ of the surface of the weld pool in a metal is described by the intersection of the sets M_L and M_s : $(x,y,z)_L \in M_L \cap M_s$.

The location of the surface of the weld pool separating the metal *M* from the surrounding gas environment *G* is determined not by temperature, but by the pressure equilibrium on the surface $Z(x,y)$ of the liquid metal M_L, therefore it is additionally described by the function $Z(x,y) \in M_L \cap G$.

The sizes of the areas and the location of the interface between them is unknown, and they must be determined during the simulation, depending on the results obtained when solving a system of equations describing the physical phenomena that occur during welding. The need for continuous adjustment of the arrangement of the interface surfaces of the selected areas during the solution, as well as a change in the arc current and their location relative to the joint, makes it necessary to solve the nonstationary problem, which considers the change in the thermodynamic state of the metal under the thermal and power effects of the welding arc. This is more convenient to carry out in a fixed Cartesian coordinate system with a central plane of symmetry, in which the metal of the welded joint is stationary, and the arcs move with the welding speed v_w in the direction of the *x* coordinate. Accordingly, the coordinates of the centers of arcs are defined as:

$$x_{a1}=x_0+v_w t;\ x_{a1}=x_{a l}-x_a;\ y_{a1}=0;\ \ y_{a2}=y(t) \quad (1)$$

where x_0 – arc initiation point; t – time since the arc initiation; $y(t)$ – function that describes the arc oscillations across the joint.

If double-sided symmetrical joint is welded with two pairs of arcs from different sides, the process is symmetrical. This allows us to limit ourselves to modeling processes on one side of the joint. At the same time, our three-dimensional analysis of heat transfer is based on the simultaneous use of two successive heat sources to account for the input heat from two separate welding arcs in the same plane.

The algorithm for virtual studying the technology of multi-arc welding of vertical joints involves establishing the spatial arrangement of the arcs in the groove, solving the heat equation and determining the location of the weld pools, solving the equilibrium equation of weld pools to achieve mass balance and spent electrode metal, determining the geometry of the welds and their quality indicators.

3. Results

In accordance with the proposed sequence of actions, we performed a computer simulation of the welding process of sheets of steel 09G2 (analogy 7Mn6 – DIN, Germany) with a thickness of 30 mm with two-sided symmetrical beveling. Shielding gas is a gas mixture. When conducting research we used electrode wire Sv-08G2S (analogy 13Mn6 – DIN, Germany) with a diameter of 1.2; 1.6 and 2.0 mm. Vertical seam, the root of the seam was welded with the movement of the torches down (vertical down), while filling the grooves with their movement up (vertical up). Stick out of 20 mm. Distance between arcs is of 30 mm.

Figure 2 shows the result of modeling the formation of the weld root during pulsed welding and electrode wire with a diameter of 1.2 mm.

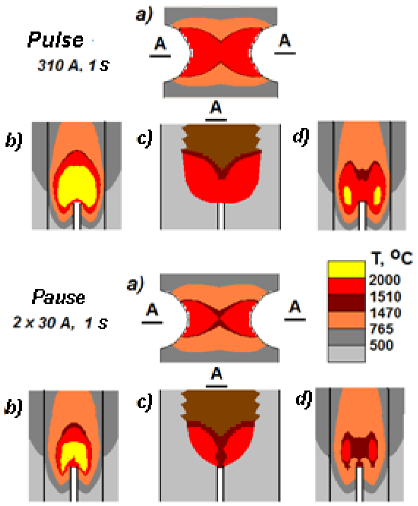

Figure 2. The result of modeling the temperature distribution at the end of the pulse and at the end of the pause during welding the root with two pulse arcs a) the temperature distribution in the weld cross section; b) on the surface of the seam; c) in the plane of symmetry; g) on the initial surface of the beveled edges.

During a root pass, it is important to ensure reliable penetration. It was found that with an enlarged root opening (up to 4 mm), more stable penetration is provided by a pulsed arc mode. An arc voltage of 30 V was chosen to obtain an arc of 3 mm in length. The accepted values are: 5.9 V – anode voltage, 6.7 – cathode voltage, 5.2 V / mm – potential gradient in the arc column. The pulse duration is 1 s, the pulse current is 310 A, the pause duration is 1 s, and the pause current is 30 A.

4. Discussion

It was found that by the end of the pulse, the mass of the weld pool increases to 12 g, and by the end of the pause it decreases almost by half – to 7 g. At the end of the pause, the weld pool partially crystallizes and lack of fusion is possible at the root of the seam (Figure 3d). But at a low welding speed, a current pulse provides a weld pool of sufficient length for complete penetration. In this case, the overlap in the center of the joint exceeds 60%. The pulsed mode increased the minimum penetration width of the root, Figure 3a, to 7 mm (versus 5 mm in continuous mode). However, the doubled arc current causes a strong heating of the electrode stick out, which forces us to recommend using a larger diameter wire (1.6 mm) during formation of root welds. In addition, with a pulsed arc, the surface of the seam has recesses, Figure 3c, which may impair the formation of subsequent layers when filling the grooves. In this case, the depth of the cavities on the seam surface is estimated to be about 1.6 mm. A significant drawback of welding with a pulsed arc with a consumable electrode is that when the arc current changes, the length of the arc gap also changes, which somewhat reduces the capabilities of pulsed technologies.

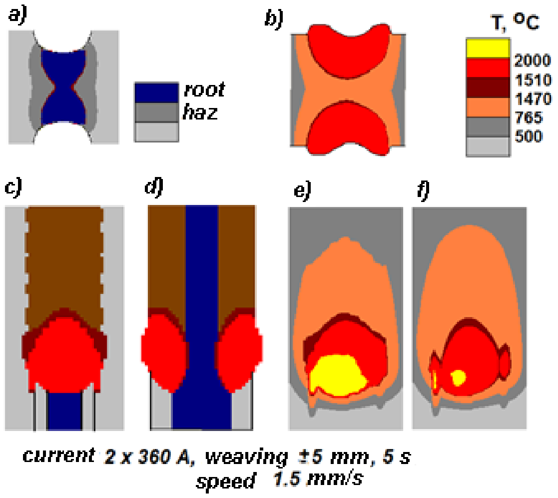

Figure 3. The simulation results of the welding of the filling passes with lateral oscillation of the electrode: a) the cross-section of the groove after the root pass; b) the maximum temperature distribution; c) temperature distribution on the weld surface; d) in the plane of symmetry; e), f) on the initial surface of the edges.

Since the root opening has a considerable width (14 mm), welding must be performed with lateral oscillations to fill it. The oscillation amplitude was set to ±3 mm, the period was 2–4 s, the delay at the edges was 0.2 s. At a speed of 1.5 mm/s, the oscillation step in the groove was 3 mm. The diameter of the electrode wire was increased to 2.0 mm, since the of the electrode stick out with a wire diameter of 1.6 mm was heated above 500 °C. It was determined that when using an electrode wire with a diameter of 2.0 mm, the temperature of stick outs does not exceed 320 °C, with a welding current of 360 A.

The simulation results of the filling passes are shown in Figure 3.

With virtual filling of the groove, an almost round weld pool with a diameter of about 16 mm is formed with the indicated welding parameters. Despite its significant weight (12 g), it is stable, since it is almost completely immersed in the groove and is held by the electrodynamic force of the arc, the value of which is estimated at 0.15 N. Nevertheless, the surface of the seam is formed with a slight convexification of about 2 mm, in the middle of which a hollow (meniscus) is located. This form of seam is allowed by regulatory documentation.

5. Conclusion

Thus, computer modeling of the features of double-sided arc welding with multiple electrodes showed that during weld formation with the movement of the electrode down (vertical down), the possibility of supplying each pair of arcs with pulsed current should be taken into account. Pulse technologies reduce the penetration sensitivity to the joint gap during the formation of the root welds. During groove filling with the movement of the electrodes up (vertical up), their lateral oscillations and delays at the edges should be carried out according to an aperiodic law in order to minimize the effects of 'magnetic blow'.

The presented results show that the proposed method for welding vertical joints has acceptable parameters, provides the required formation of the seam and can be used during tanks assembling. In addition, the use of the presented physical and mathematical model for virtual reproduction of the process of automatic double-sided welding of vertical joints will solve all main problems in the

IOP Conf. Series: Materials Science and Engineering **966** (2020) 012014 doi:10.1088/1757-899X/966/1/012014

development of technologies and the necessary equipment for welding vertical joints of tanks with thick shells for storing large volume oil and oil products.

Acknowledgement
The assistance provided by the translator of the present article Ms. Natalia Karamysheva was greatly appreciated.

References
[1] Safina I, Kauzova P and Gushchin D 2016 Otsenka tekhnicheskogo sostoyaniya rezervuarov vertikalnykh stalnykh [In Russian] *Tech Nadzor* **3** pp 40–1
[2] Bezborodov Yu, Shram W and Kravtsova E 2015 *Rezervuary dlya priyema, khraneniyai otpuska nefteproduktov* [In Russian] (Krasnoyarsk) p 108
[3] Kah P and Martikainen J 2011 Current trends in welding processes and materials: Improve in effectiveness *Reviews on Advanced Materials Science* **30 2** pp 198–200
[4] Sakamoto R, Kobayashi K, Iijima T, Nishimura Y and Mizo Y 2010 Development of vertical submerged arc welding method for aboveground LNG storage tank construction *Ishikawajima-Harima Engineering Review* **43 2** pp 55–62
[5] Kunina P, Velichko E, Prikhodko M and Nizhnik A 2017 Razrabotka sovremennykh metodik diagnostiki svarnykh soyedineniy rezervuarov dlya khraneniya neftiinefteproduktov metodom ul'trazvukovogo kontrolya [In Russian] *Territoriya Neftegaz* **1** pp 20–4
[6] Goncharov N, Nesterov G and Yushin A 2019 Issledovaniye defektov svarnykh shvov rezervuarov vertikalnykh stalnykh [In Russian] *Bezopasnost' truda v promyshlennosti* **3** pp 69–74
[7] Filippov O 2020 Puti sovershenstvovaniya svarochnykh rabot pri stroitel'stve rezervuarov dlya khraneniya nefti i nefteproduktov [In Russian] *Blanking Productions in Mechanical Engineering* **17 7** (in the editorial portfolio)
[8] Cho D, Na S, Cho M and Lee J 2013 A study on V-groove GMAW for various welding positions *Journal of Materials Processing Technology* **213 9** pp 1640–52
[9] Scotti A, Larson U and Norrish J 1991 Bead instability of mechanized P-MIG [pulsed MIG] welding in vertical-up position *International Journal of the Joining of Materials* **3 1** pp 18–24
[10] Fiveyskii A, Buzorina D, Melnikov A and Filyakov A 2016 Sovershenstvovaniye vysokoproizvoditelnykh protsessov impulsnoydugovoy svarki v zashchitnykh gazakh [In Russian] *Svarkai Diagnostika* **6** pp 53–5